Starshade Technology Readiness

Presentation to Astro 2020 NAS Decadal Committee

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November 19, 2019

Jet Propulsion Laboratory
California Institute of Technology

NASA Charters Starshade Technology Activity (March 2016)

Technology Activity Goals:

- "to mature the required techniques to the point at which starshades could be integrated into potential future exoplanet detection and characterization missions"

- *Advance critical capabilities and close key technology gaps* to TRL5:*
  - *Starlight suppression*
  - *Formation flying*
  - *Deployment of large-scale, precision structures*

** reference ExEP Technology Plan Appendix*

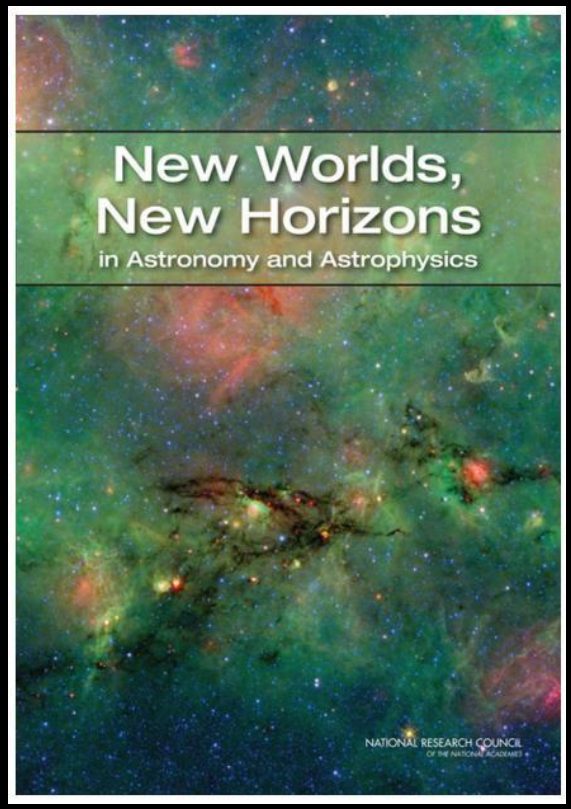
Programmatic Context

2010 Decadal Called for Technology Investment

Decadal Survey Recommendation:

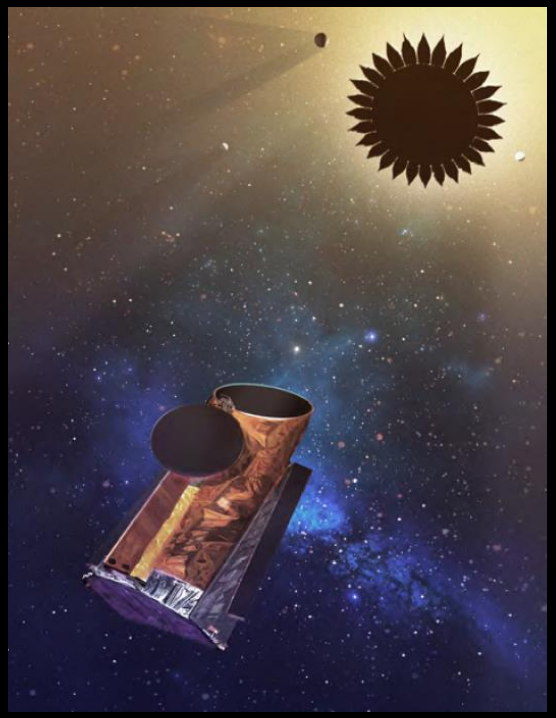
"Candidate starlight suppression techniques be developed to a level such that mission definition for a space-based planet imaging and spectroscopy mission could start late in the decade."

- **APD Response:**
  - Strategic Astrophysics Technology (SAT) program
    - Competitively selected individual investigator awards to address mid-TRL technologies (3-5)
  - In 2016, the starshade was spun off to establish a starshade technology development activity with the goal of advancing starshade technology to TRL 5



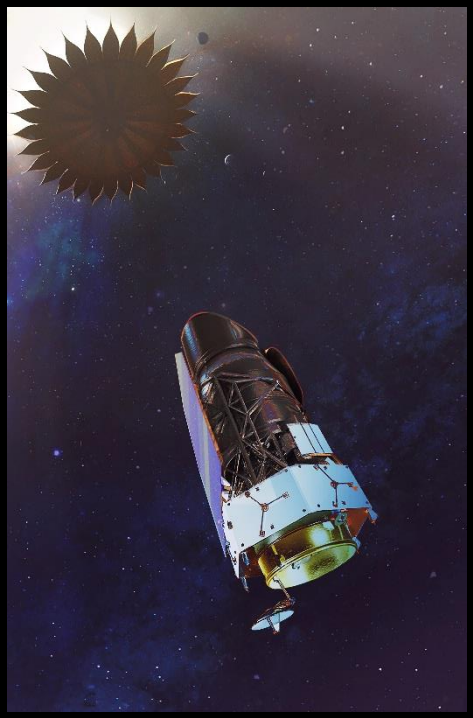
Reference Mission Concepts for Starshade Technology

Habitable Exoplanet Observatory



Telescope Diameter 4 m
Starshade Diameter 52 m
Separation 76,600 km
IWA 70 mas

WFIRST-Rendezvous Probe



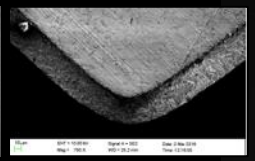
Telescope Diameter 2.4 m
Starshade Diameter 26 m
Separation 26,000 km
IWA 103 mas

NASA 7123.1B Appendix E – TRL Definitions

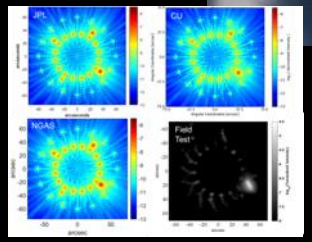
TRL	Definition	Hardware Description	Software Description	Exit Criteria
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrate overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.

The Three Starshade Technology Gaps

(1) Starlight Suppression

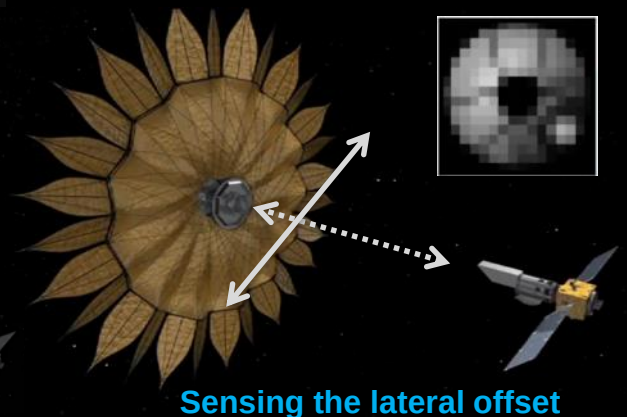


Suppressing scatted light off petal edges from off-axis Sunlight (S-1)



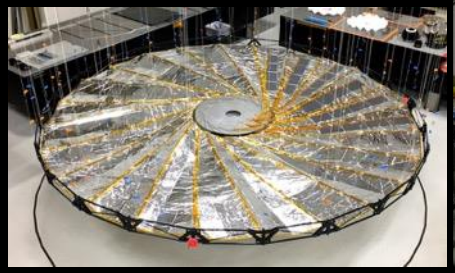
Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

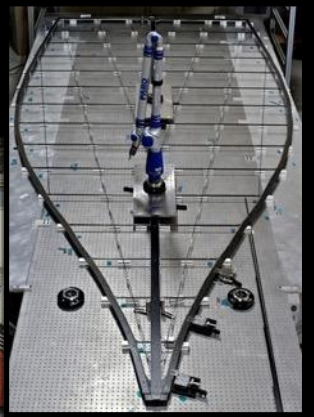
(2) Formation Sensing



Sensing the lateral offset between the spacecraft (S-3)

(3) Shape Accuracy and Shape Stability



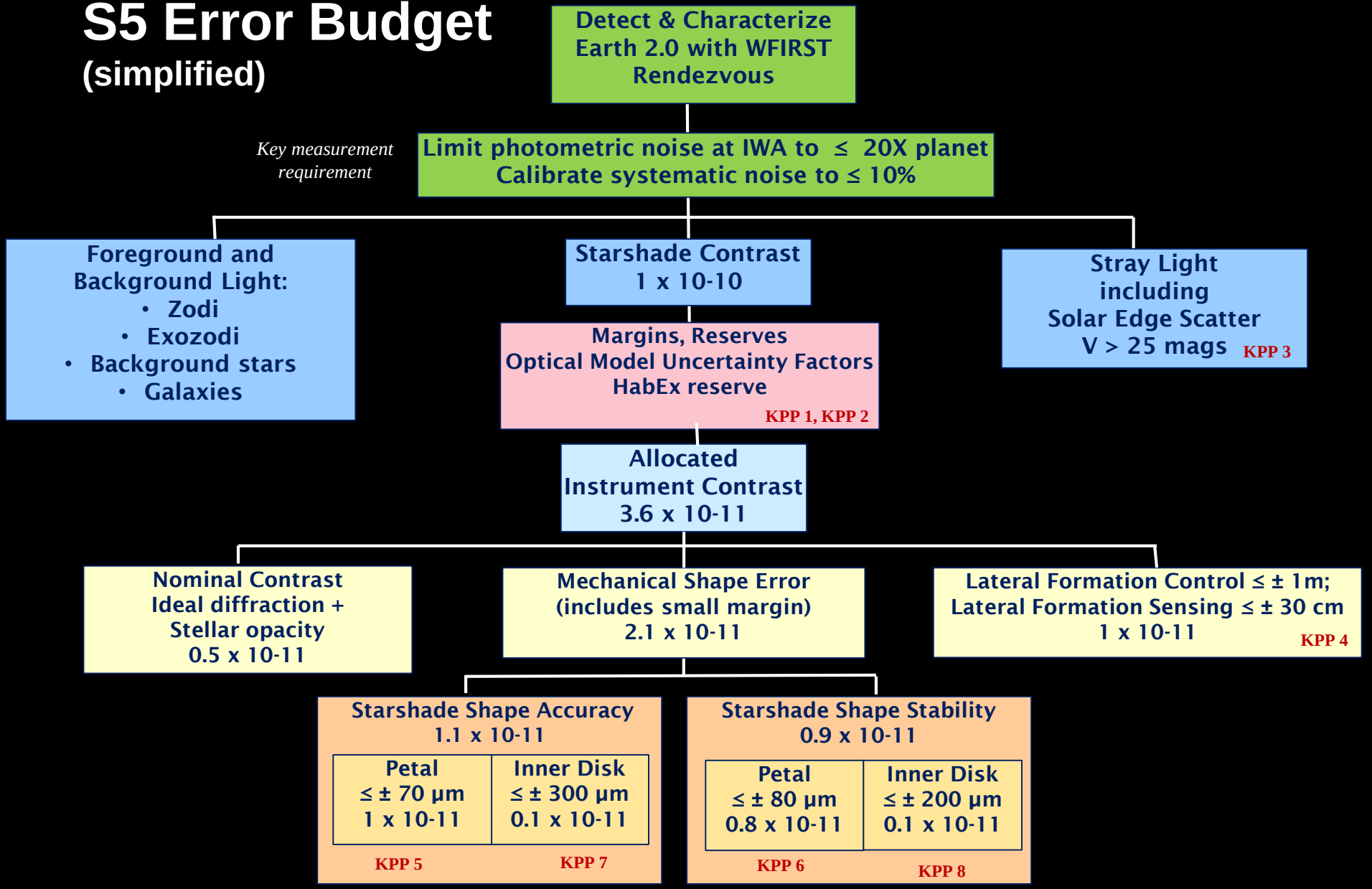


Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)

Fabricating the petals to high accuracy (S-4)

S-# corresponds to ExEP Starshade Technology Gap (http://exoplanets.nasa.gov/exep/technology/gap-lists)

S5 Error Budget
(simplified)



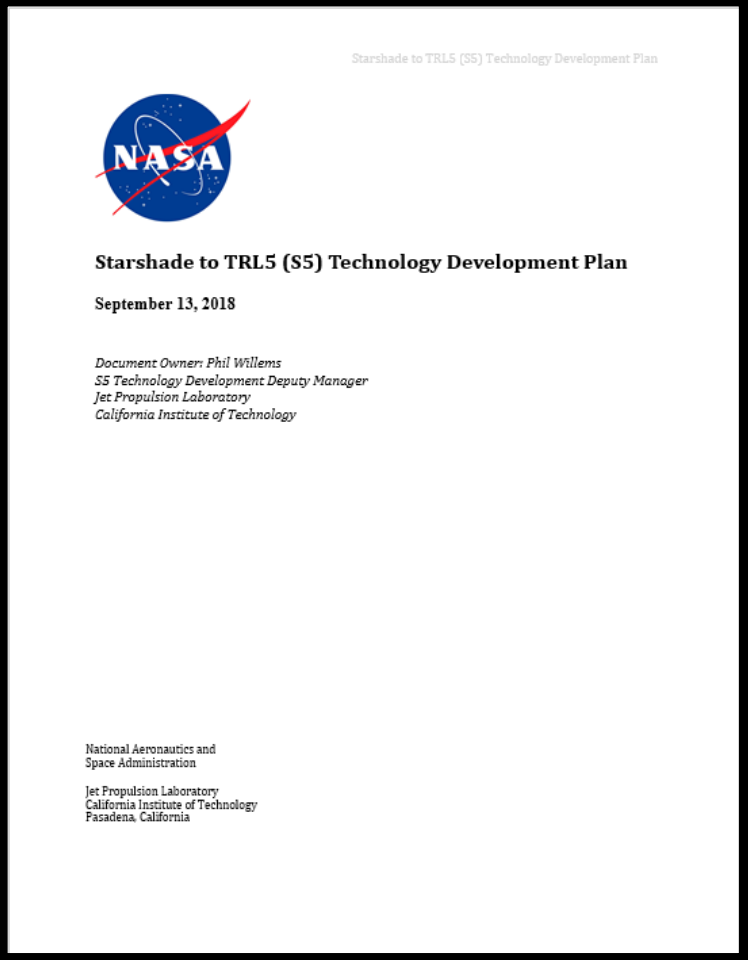
KPP = Key Performance Parameter, a measurable performance level applied to a technology needed by a mission concept

Something for Fidelity and Scale of HW

Starshade Definition of TRL 5

Technology Gap Area	KPP	Fidelity			Relevant Environments	Verification	Model Validation
		Form	Fit	Function			
Starlight Suppression	Demonstrate flight instrument contrast is viable via subscale lab tests at **≤ 1 x 10^{-10}** Validate contrast senstivity to accuracy of **≤ ± 25%**	Flight-like shape, etched in silicon	1/500th scale, near-flight Fresnel #	Flight-like diffraction perf.	Space, large telescope distance	Measure image plane contrast at multiple wavelengths covering flight bandpass. Introduce precisely known shape errors, measure contrast at the 10^{-8} to 10^{-9} level, extrapolate to flight	Demonstrates all physics are captured Validates model used to establish all shape error allocations
Lateral formation sensing & control	Verify sensing accuracy to **≤ ± 30 cm** (1/8th pupil dia.) & corresponding control to **≤ ± 1m**, via simulation	Flight-like shape, copper on glass	1/4000th scale, near-flight Fresenel #	Flight-like diffraction perf.	Space, large telescope distance, ≤ 1 µg gravity gradient	Measure lateral shear in pupil plane of Poisson spot from out of band starlight. Verify control perf. via simulations using a validated	Validates prototype lateral sensor algorithms.
Solar Scatter	Verify lobe brightness is dimmer than **25 visual magnitudes**	Medium fidelity optical edge segment.	3/4 scale	Flight-like scatter perf., in-plane shape profile	Deploy cycles, thermal cycles, dust in lab &	Measure scatter at discrete Sun angles & measure in-plane profile, after env. Tests	Validates model of scatter vs. Sun angle at edge coupon level.
Petal Shape	Pre-launch shape accuracy (manufacture, AI&T, storage) **≤ ± 70 µm** On-oribt thermal stability **≤ ± 80 µm**	Med. fidelity Petal Subsystem, all features & interfaces	3/4 scale	Flight-like	Deploy cycles, thermal cycles, stowed storage, temperature	Measure shape before & after env. tests, Measure petal critical dimensions in ambient press. "hot box" vs. temperature	Validates models of: shape vs. temp, shape vs. I/F load, creep vs. time & temperature.
Petal Position	Pre-launch shape accuracy (manufacture, AI&T, storage) **≤ ± 300 µm** On-oribt thermal stability **≤ ± 200 µm**	Med. fidility Inner Disk Subsystem, all features & interfaces	Full-scale	Flight-like	0-gravity, space vacuum, stowed storage, temperature	Measure petal position after many quasi-static deployments that min. air drag and imperfect gravity off- Measure Truss-Bay critical dimensions in ambient press. "hot box" vs. temperature	Validates models of: shape vs. temp, shape vs. I/F load, creep vs. time & temperature.

Technology Development Plan & Milestones


Starshade to TRL5 (S5) Technology Development Plan

Starshade to TRL5 (S5) Technology Development Plan

September 13, 2018

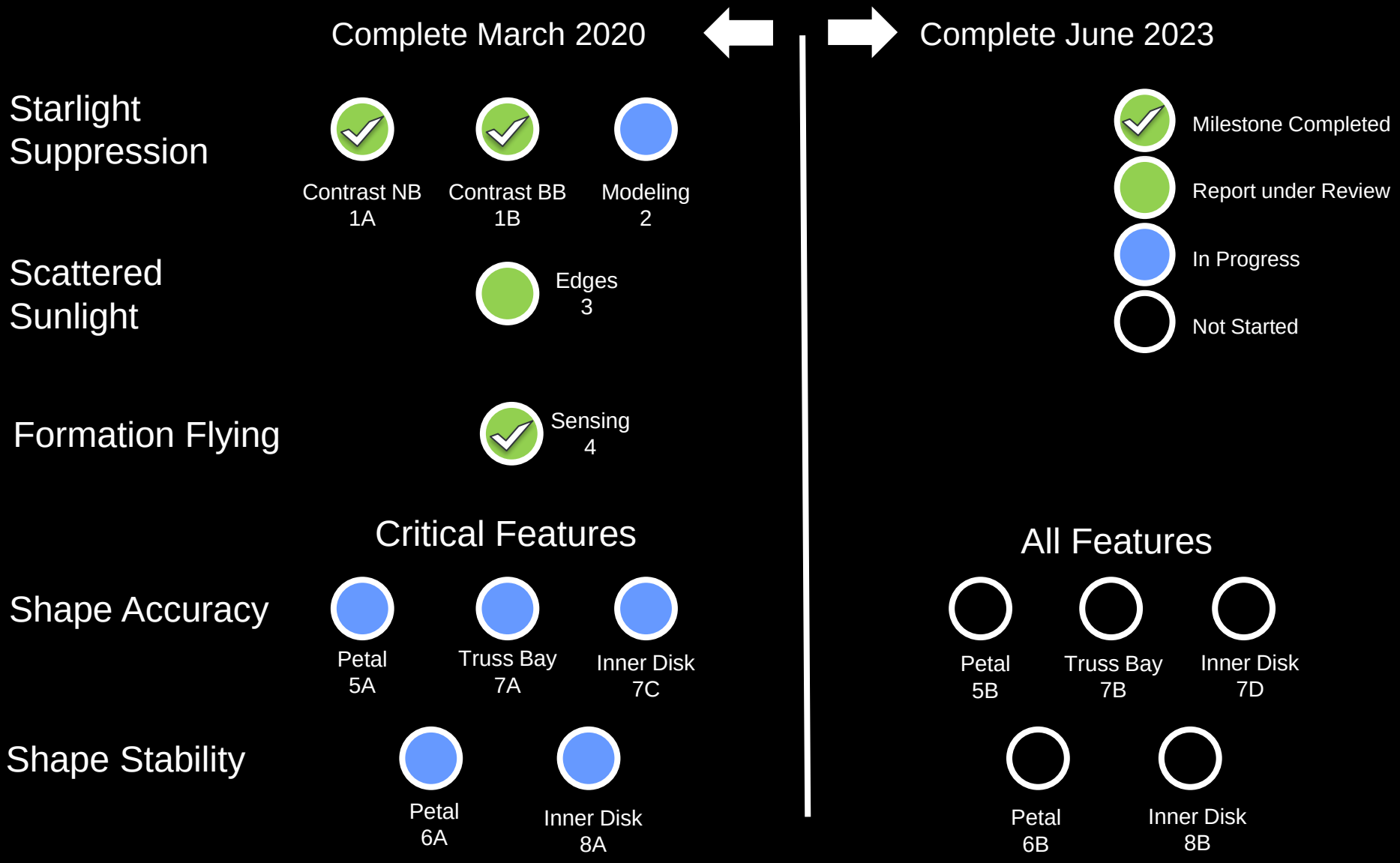
Document Owner: Phil Willems
S5 Technology Development Deputy Manager
Jet Propulsion Laboratory
California Institute of Technology

National Aeronautics and
Space Administration

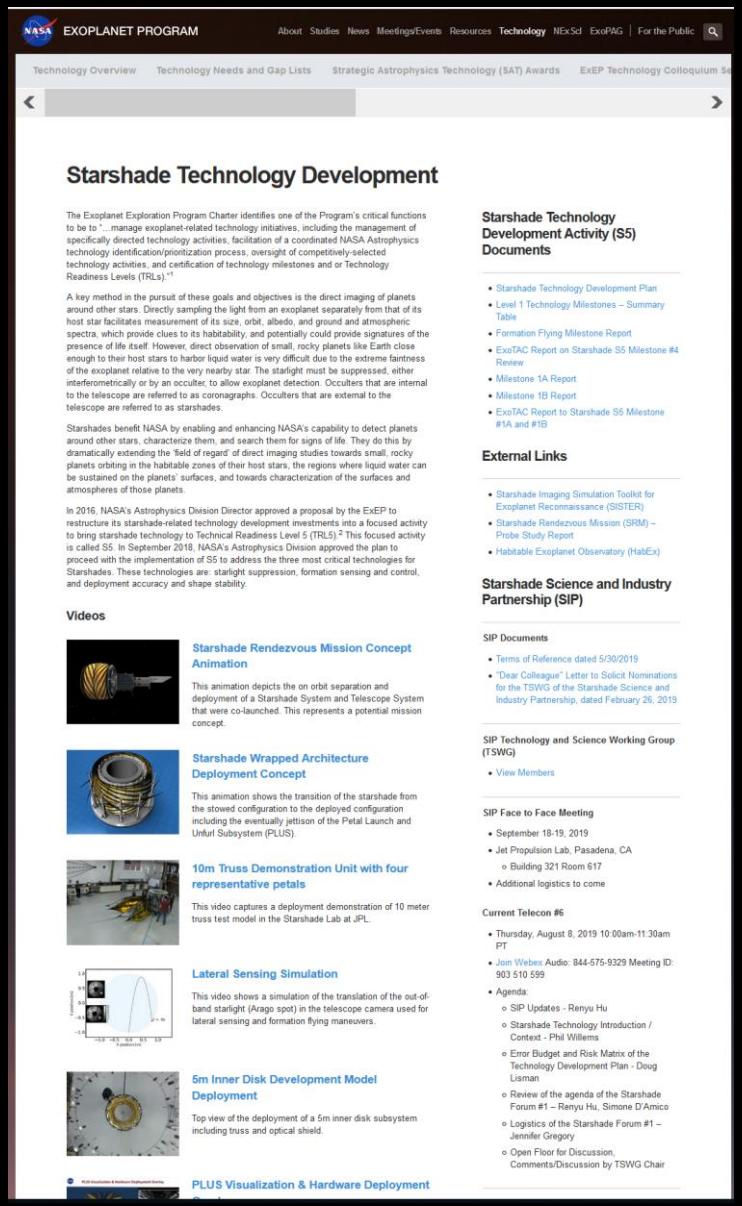
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

MS	Short Text	KPP
1A	Optical Contrast – Narrowband	10^{-10}
1B	Optical Contrast – Broadband	10-10
2	Optical Model Validation	25%
3	Scattered Sunlight	Vis Mag > 25
4	Lateral Sensing	+/- 30 cm
5A	Petal Shape Accuracy – Crit Features	+/- 70 μm
6A	Petal Shape Stability – Crit Features	+/- 80 μm
7A	Truss Bay Accuracy – Crit Features	+/- 200 μm
7C	Inner Disk Accuracy – Crit Features	+/- 200 μm
8A	Inner Disk Stability – Crit Features	+/- 300 μm
5B	Petal Shape Accuracy – All Features	+/- 70 μm
6B	Petal Shape Stability – All Features	+/- 80 μm
7B	Truss Bay Accuracy – All Features	+/- 200 μm
7D	Inner Disk Accuracy – All Features	+/- 200 μm
8B	Inner Disk Stability – All Features	+/- 300 μm

S5 Technology Milestones Scorecard



Public Dissemination of S5 Results



- A Starshade Technology web-page within the ExEP web portal

https://exoplanets.nasa.gov/exep/technology/starshade/

- Provides the following data types:
  - S5 Technology Development Plan
  - Milestone Reports and ExoTAC Reviews
  - Starshade Technology Status Report
  - Forum Presentations (webex and F2F)
  - Links to relevant publications and webpages
  - Starshade graphics, videos and other materials

- Milestone results alsp published in technical journals and presented at conferences.

Technical approach

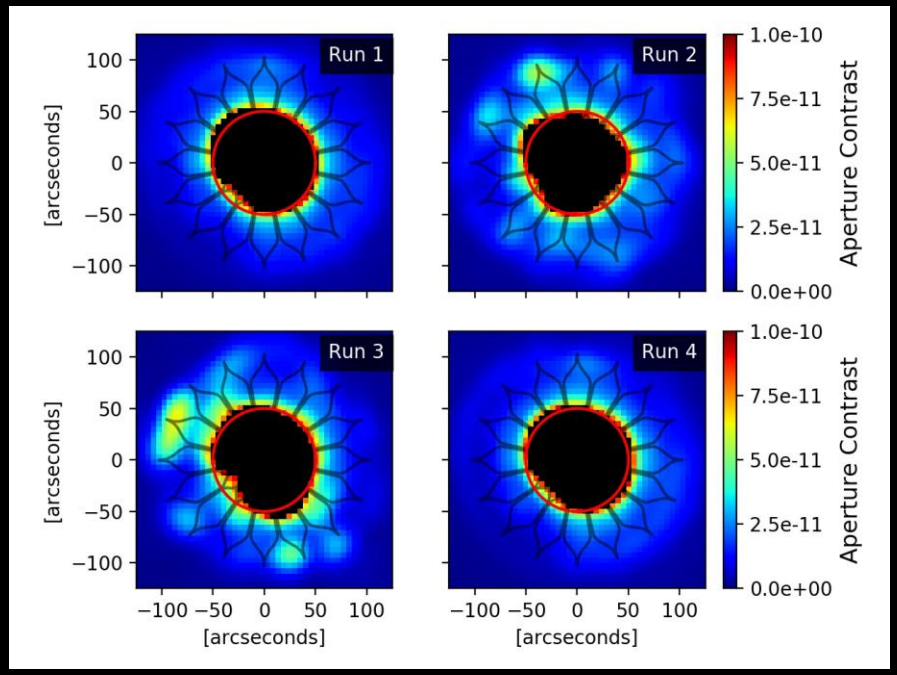
- Requirements and performance are driven by near term science and mission needs
  - WFIRST Rendezvous and HabEx are ApD supported and well defined.
- Complete error budget accounts for all errors and system effects
  - Estimate or bound non-starshade items
  - Focus on key performance parameters to be demonstrated
  - Margins and uncertainties included within the error budget
    - Allows KPPs to satisfy both WFIRST and HabEx requirements.
- Milestones address performance and completeness requirements of TRL 5 for all technologies
  - Define TRL 5 relevant to HW fidelity and test environment
  - Include system performance modeling to address TRL 5 performance at a system level

Technology Status

Narrow band Contrast Demonstration

Small scale starshade mask in the Princeton Testbed demonstrates $1x10^{-10}$ instrument contrast at the inner working angle in narrow band visible light and Fresnel number ≤ 15.

KPP 1



REQUIREMENT MET: Achieved $<10^{-10}$ contrast at 44% of IWA, best performance to date of a starshade at a flight-like Fresnel number.

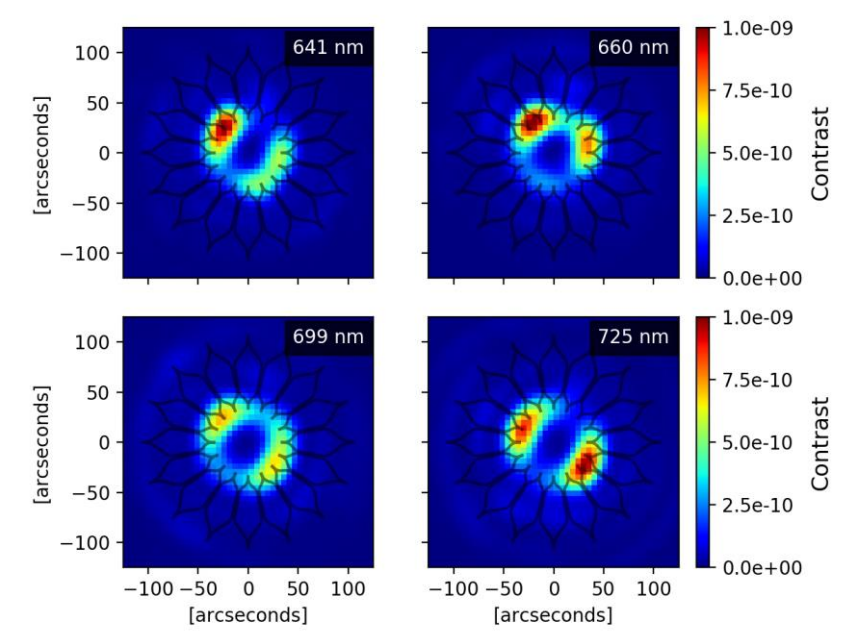
Limits to contrast at small scale are well understood.

STATUS: Complete

Broad band Contrast Demonstration

Small-scale starshade mask in the Princeton Testbed demonstrates 1 × 10^{-10} instrument contrast at the inner working angle at *multiple wavelengths* spanning ≥ 10% bandpass and Fresnel number ≤ 15 at the longest wavelength.

KPP 1



REQUIREMENT MET: Achieved <10^{-10} contrast at IWA for all wavelengths tested

STATUS: Complete

Optical Contrast Model Correlation

Small-scale starshade masks in the Princeton Testbed validate contrast vs. shape model to within 25% accuracy for induced contrast between 10^{-9} and 10^{-8}.

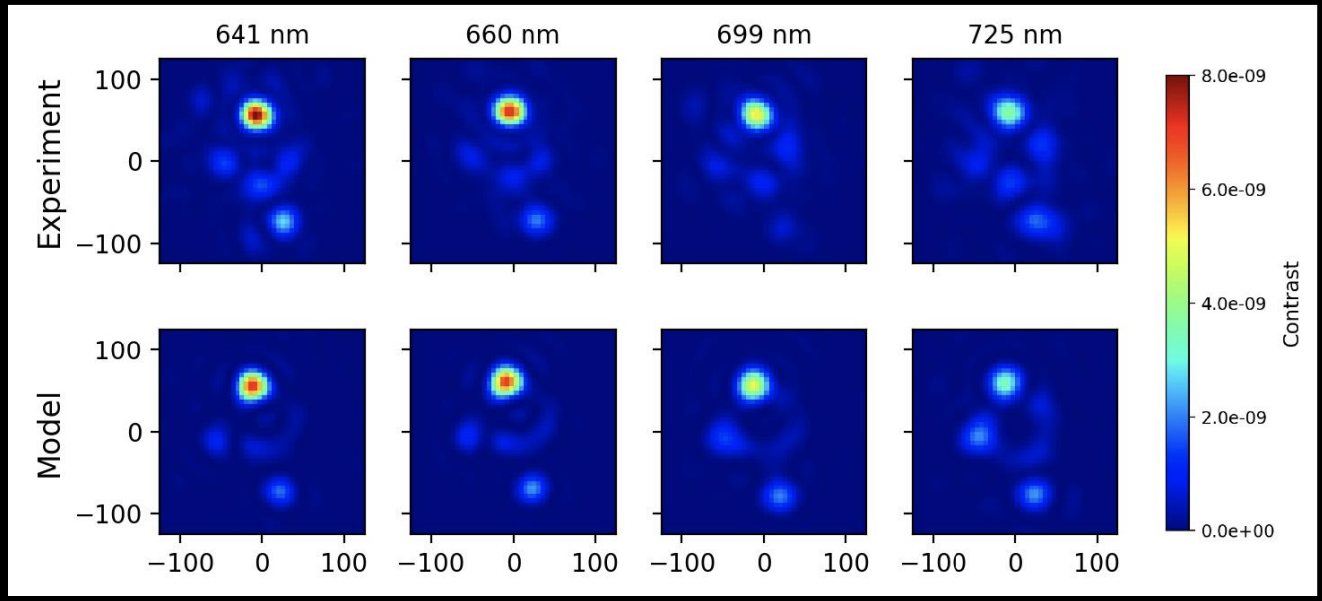
KPP 2

APPROACH:

Test deliberately misshapen masks to verify that contrast varies with shape error as predicted

STATUS:

Contrast varies with shape as expected in masks tested to date



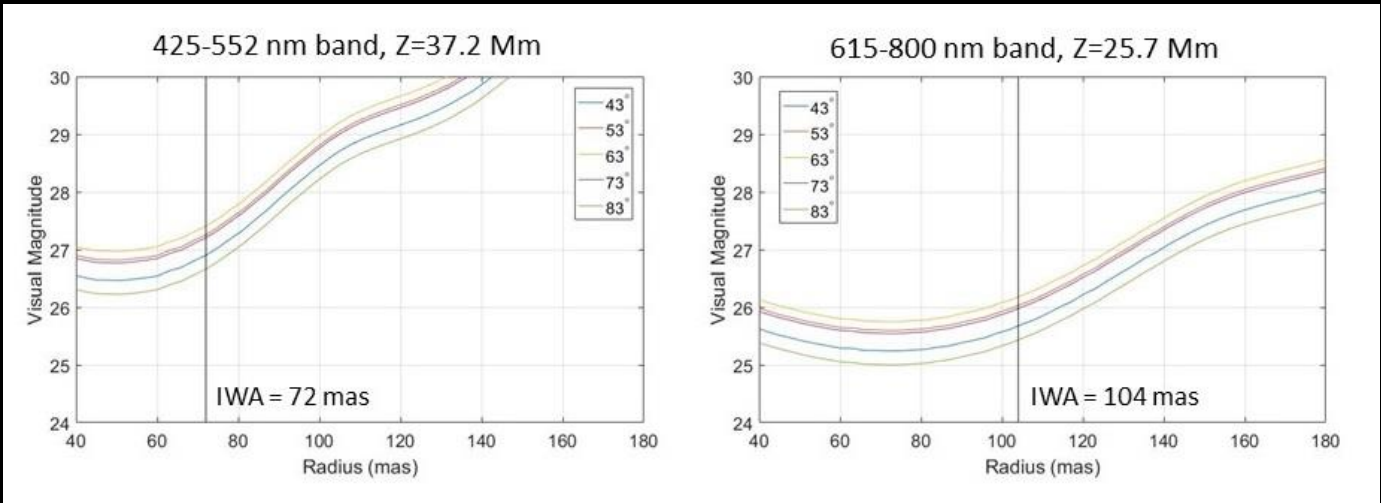
Solar Glint

Optical edge segments demonstrate scatter performance consistent with solar glint lobes fainter than visual magnitude 25 after relevant thermal and deploy cycles.

KPP 3

RESULTS:

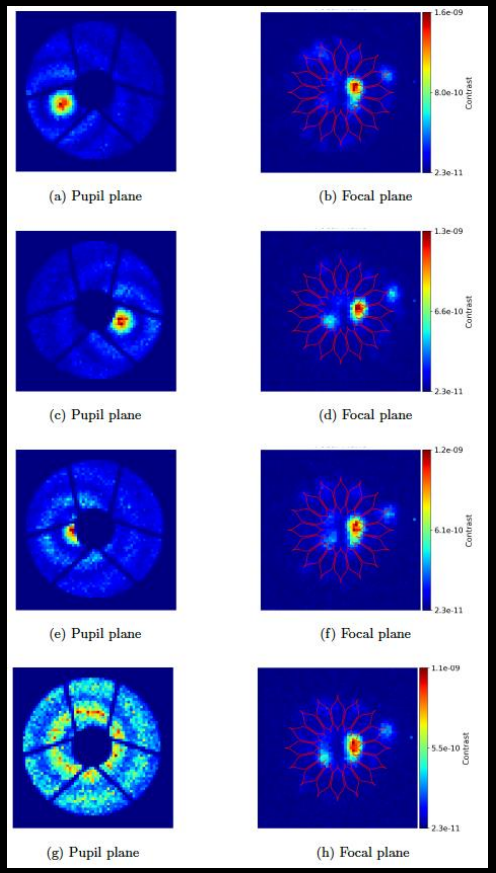
- No degradation in scatter performance after exposure to environments
- System model shows scatter lobe dimmer than V=25 mag for all wavelengths and sun angles



STATUS: In review

Formation Flying

Starshade Lateral Alignment Testbed validates the sensor model by demonstrating lateral position offset sensitivity to a flight equivalent of 30cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ±1m.



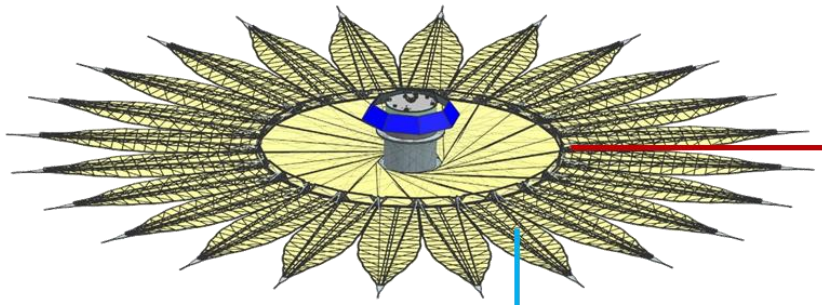
KPP 4

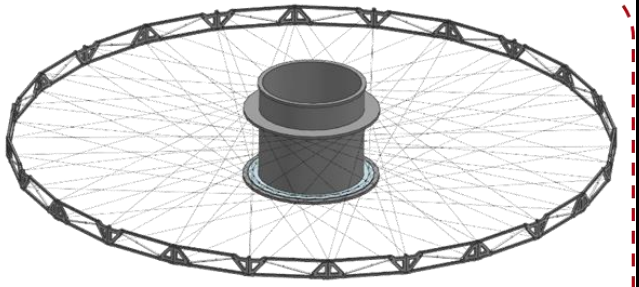
REQUIREMENT MET:

- Starshade lateral offset measured to 10cm flight equivalent.
- Formation flying simulation controlled position to ±1m
- Large margins on stellar magnitude, allowable measurement error

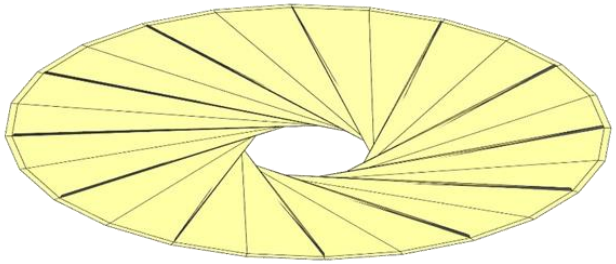
STATUS: Complete, formation flying at TRL5

Starshade Structural Subsystems



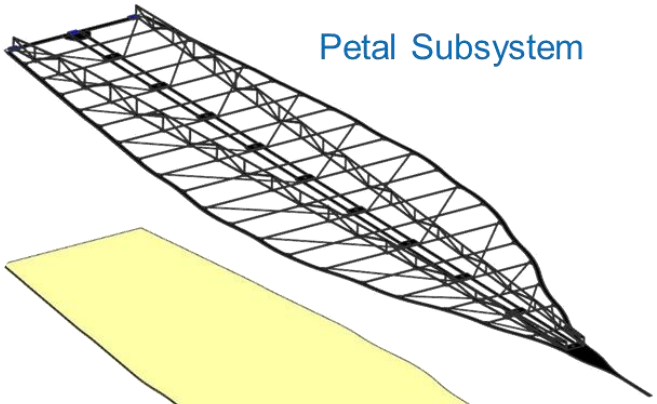


Truss + spokes + hub constitute separable structure w/defined interfaces to petal



Inner Disk Subsystem

Petal Subsystem

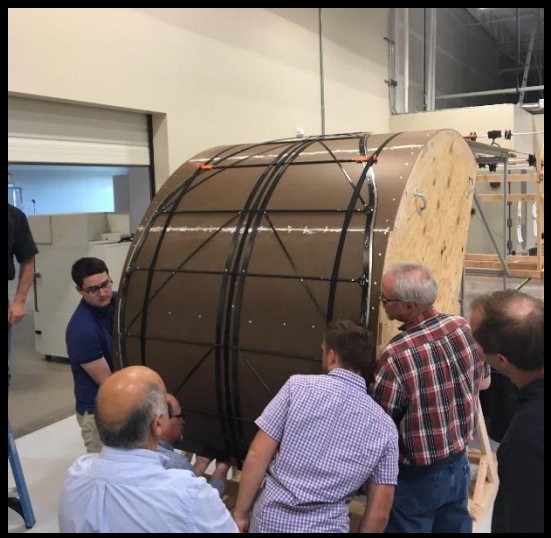


Petal Sub-assembly developed, manufactured and assembled separably from inner disk, with defined interfaces at its base

Structural technology development approach: build and test initial prototypes having *shape critical* features, then build on experience with prototypes with *all* features

Starshade Shape Accuracy- Petal

Petal subsystem demonstrates total prelaunch shape stability (manufacture, deploy cycles, thermal cycles deployed, and storage) consistent with a total pre-launch shape accuracy within ±70 μm.



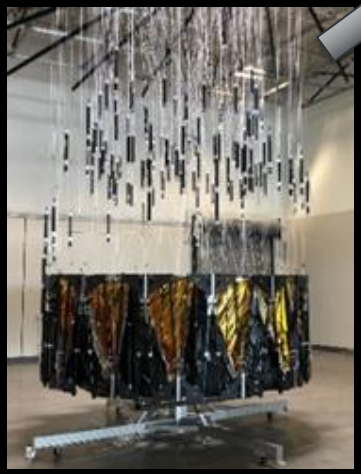
RESULTS:

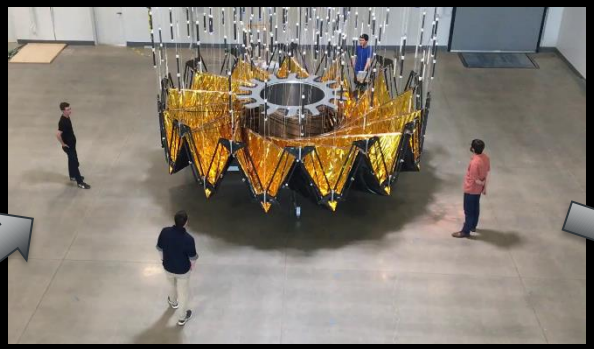
Shape-critical element prototype meets requirement after stow-and-deploy and thermal cycles

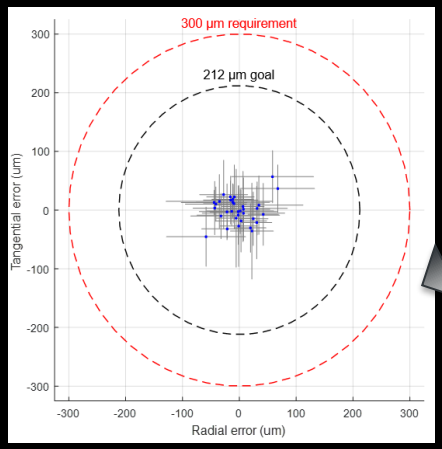
First article 12/2019, TRL5 by 6/2023

Starshade Shape Accuracy- Inner Disk

Truss Bay assembly demonstrates dimensional stability with thermal cycles (deployed) and storage consistent with a total pre-launch petal position accuracy within ±300 µm.
Inner Disk Subsystem with optical shield assembly demonstrates repeatable accuracy consistent with a total prelaunch petal position accuracy within ±300 µm.

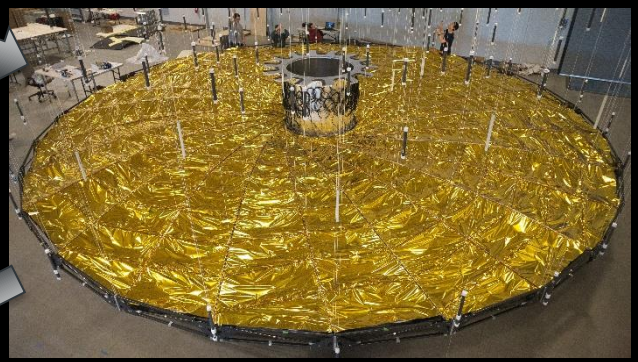






RESULTS:

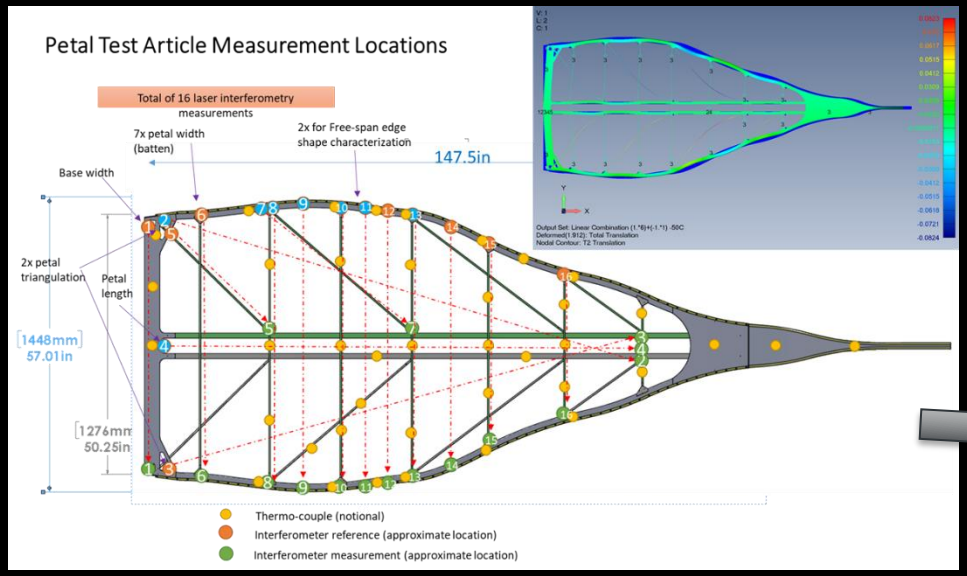
Shape-critical element prototypes meet requirement after stow-and-deploy cycles, subassembly thermal cycles



First articles 12/2019, TRL5 by 6/2023

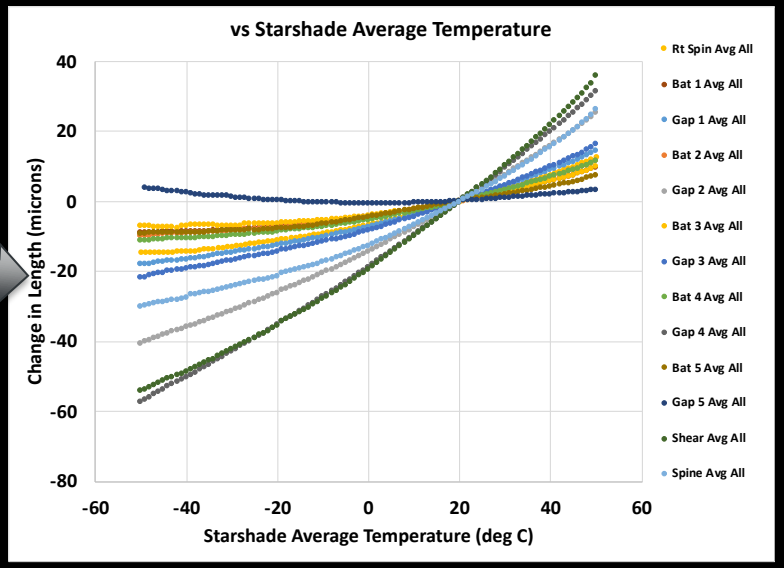
Starshade Shape Stability- Petal

Petal subsystem demonstrates on-orbit thermal stability within ±80 µm by analysis using a validated model of critical dimension vs. temperature.



RESULTS:

Shape-critical element prototype meets requirement with large margin.



First article 12/2019, TRL5 by 6/2023

Starshade Shape Stability- Inner Disk

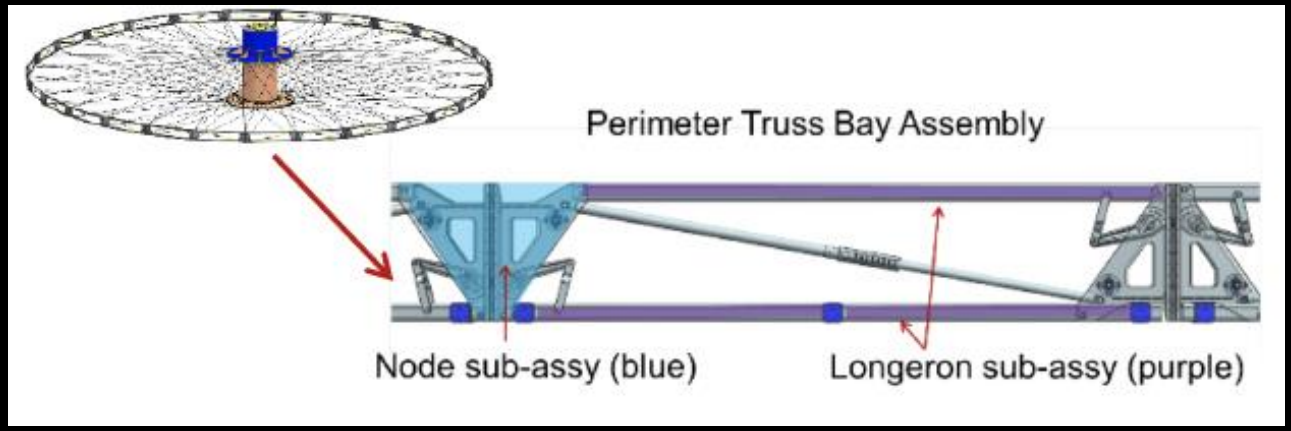
Truss Bay assembly demonstrates on-orbit thermal stability within ±200 µm by analysis using a validated model of critical dimension vs. temperature.

APPROACH:

- Initial tests verify stability of longeron and node subassemblies
- Final TRL5 test verifies stability of complete truss bay assembly

RESULTS:

Longerons and nodes meeting requirements with margin.



First articles 12/2019, TRL5 by 6/2023

S5 Technology Milestones – Near Term

Defines achievement of TRL 5 for all Technology Gaps

Technology Gap S-1 Starlight Suppression			**TRL5**
MS#1A	Demo contrast 1E-10 IWA, F<15 narrow band	Jan 2019	COMPLETE
MS#1B	Demo contrast 1E-10 IWA, F<15 broad band	Mar 2019	COMPLETE
MS#2	Optical Model correlation to 25% accuracy	Mar 2020	In Process
Technology Gap S-2 Scattered Sunlight			**TRL5**
MS#3	Edge scatter Vmag<25 BAE	Nov 2019	In process
Technology Gap S-3 Lateral Sensing			**TRL5**
MS#4	Demo lateral sensing to 30cm; Control sim to 1m	Nov 2018	COMPLETE
Technology Gap S-4 Petal Shape Accuracy and Stability			**TRL4+**
MS#5A	Petal (critical features) shape accuracy to 70um BAE	Dec 2019	In process
MS#6A	Petal (critical features) on orbit shape stability to 80um	Dec 2019	In process
Technology Gap S-5 Petal Position Accuracy and Stability			**TRL4+**
MS#7A	Truss sub-assy HW thermal dimensional stability	Dec 2019	In process
MS#7C	IDS (crit features) deployment repeatability 300um	Dec 2019	In process
MS#8A	Truss sub-assy on orbit thermal stability 200um	Dec 2019	In process

* BAE = Before and After Environments

S5 Technology Milestones – Longer Term

Defines achievement of TRL 5 for all Technology Gaps

Knowledge gained from early mechanical milestones will be incorporated into design before beginning fabrication of “full scale” mechanical test articles.

Technology Gap S-4 Petal Shape Accuracy and Stability — **TRL5**

MS#5B	Petal (all features) shape accuracy to 70um BAE	Jun 2023
MS#6B	Petal (all features) on-orbit shape stability to 80um	Jun 2023

Technology Gap S-5 Petal Position Accuracy and Stability — **TRL5**

MS#7B	Truss Assy HW thermal & storage dimensional stability	Jun 2023
MS#7D	IDS (all features) deployment repeatability 300um	Jun 2023
MS#8B	Truss Assy on orbit thermal stability 200um	Jun 2023

Summary

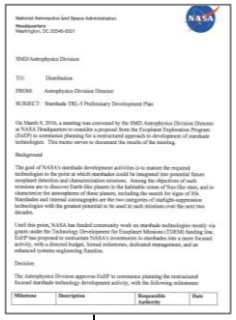
- S5 results to date consistent with high margin for exoplanet mission science yields
- S5 Milestones and Key Performance Parameters broadly applicable to proposed starshade missions operating at Earth-Sun L2 orbit
- S5 (and ExEP) is ‘keeping an open mind’ via its Science and Industry Partnerships and Assessment Reviews- as starshade mission space evolves, S5 will evolve with it

Jet Propulsion Laboratory
California Institute of Technology

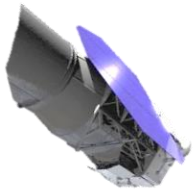
This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

BACKUP

Two Years of Planning (and technical progress)



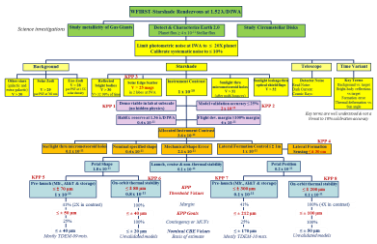
Astrophysics Probe Studies
Starshade Rendezvous
Mission SRM
PI: Seager/Kasdin



Status Review

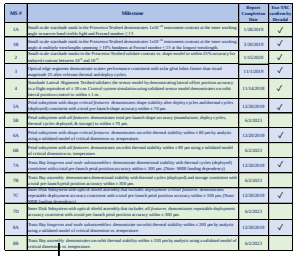
Dec'17

(FF, scatter, suppression)
Nov17-Mar18



Key Performance Parameter Review with Mission Stakeholders

Milestone Review with ExoTAC



Mar'16

Jun'17

Jul18

Aug18

Dec'16 Mar'17 Apr'17 Oct'17

Oct'17-May'18

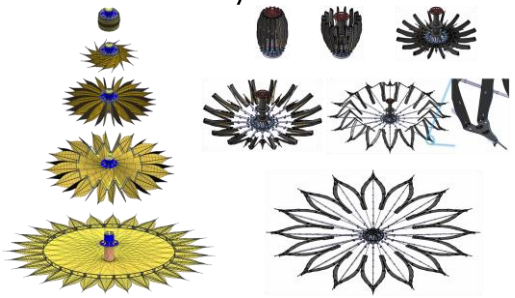
Aug18

Aug18

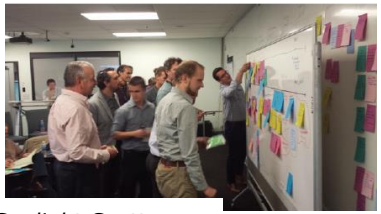
Sep 2018

Community Kickoff

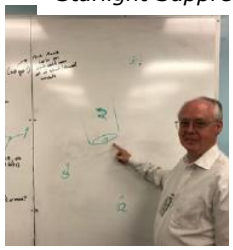
Starlight Suppression



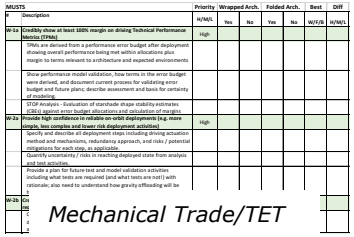
Cost Review



Sunlight Scatter



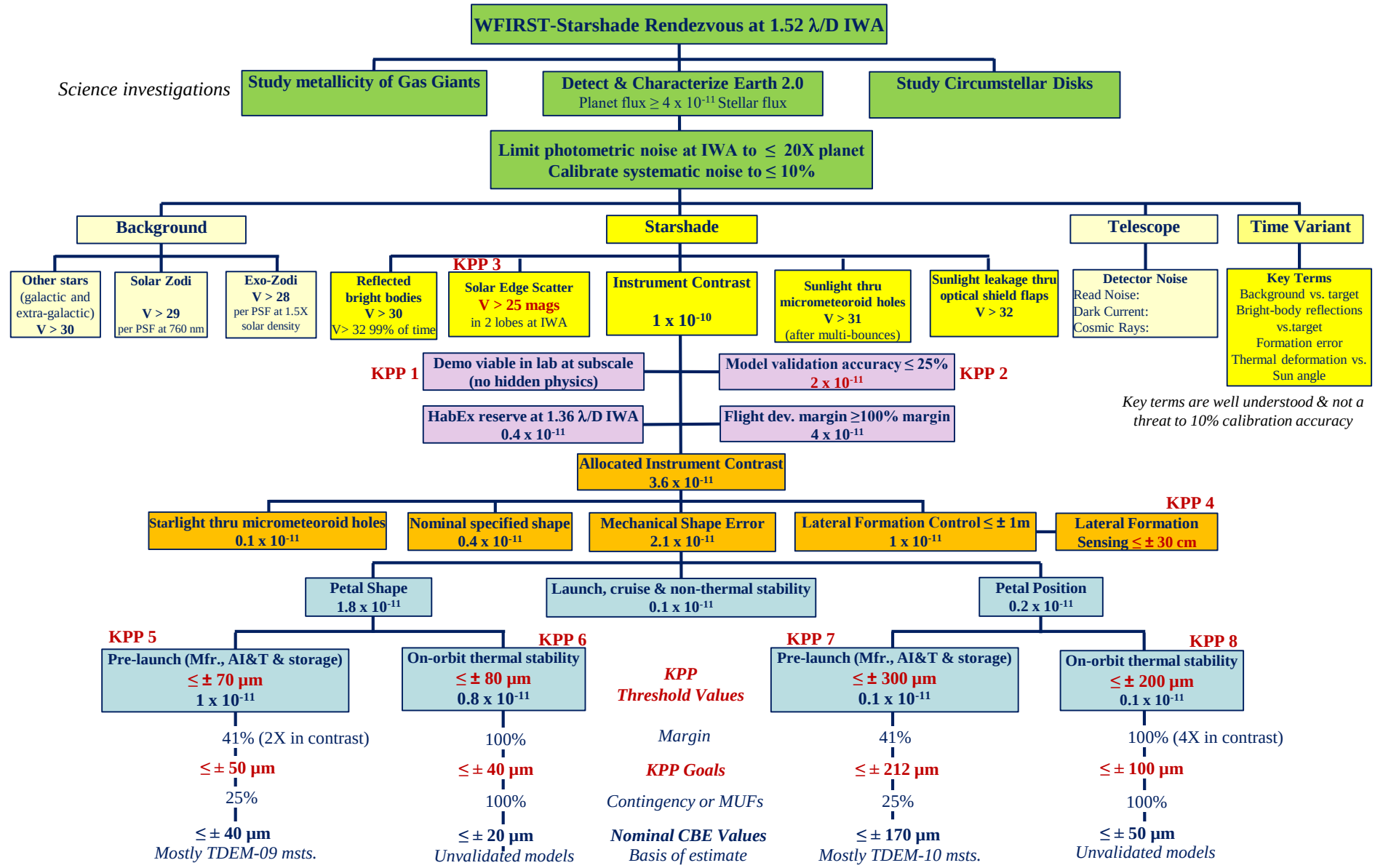
Mechanical



Mechanical Trade/TET

APPROVED

S5 Error Budget Tree



What Is Technology Readiness Level 5?

Per “JPL Technology Readiness Assessment Guide” published in IEEE in 2016

Definition from NPR 7123.1e	Component and/or brass-board validated in relevant environment
Completion Criteria from NPR 7123.1e	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
Mission Req.	Generic or specific class of missions
Technology Gaps	Assess technology readiness and identify Technology Gaps
Performance/ Function	Basic functionality/performance maintained
Fidelity of Analysis	Medium fidelity: to predict key performance parameters and life limiting factors as a function of relevant environments
Fidelity of Build	Medium fidelity: brass-board with realistic support elements
Level of Integration	Component/ Assembly
Environment Verification	Tested in relevant environments. Characterize physics of life-limiting mechanisms and failure modes.